Int. J. Environ. Sci. Tech., 8 (2), 373-380, Spring 2011
ISSN: 1735-1472

Accuracy assessment of moderate resolution image spectroradiometer products for dust storms in semiarid environment

[1*] ***J. Amanollahi;*** [2] ***S. Kaboodvandpour;*** [1] ***A. M. Abdullah;*** [1] ***M. F. Ramli***

[1] *Department of Environment science, Faculty of Environmental studies, Universiti Putra Malaysia, Serdang, Selangor, Malaysia*

[2] *University of Kurdistan, Sanandaj, Iran*

Received 6 September 2010; revised 25 January 2011; accepted 15 February 2011; available online 1 March 2011

ABSTRACT: Dust storms are strongly and negatively associated with the annual cycle of rainfall and coincide with the west and southwesterly winds in west and south west of Iran. Accuracy assessment of particulate matter products of moderate resolution image spectroradiometer was studied in this research. Moderate resolution image spectroradiometer products consist of aerosol optical thickness, its corresponding image red, green and blue and moderate resolution image spectroradiometer/ terra calibrated radiances 5 minutes L1B swath 1 km, which shows the environmental information at terrestrial, atmospheric and ocean phenomenology. Daily aerosol optical thickness data retrieved from moderate resolution image spectroradiometer from May 2009 to May 2010 were compared with the amount of particulate matter measured at ground in Sanandaj, Iran, using non-linear correlation coefficient. Results showed that the moderate resolution image spectroradiometer image / terra calibrated radiances 5 minutes L1B swath 1 km is able to detect dust storms distribution and their blowing direction over study area clearly. The air quality conditions obtained in with dust storm period were unhealthy and correlation coefficients between moderate resolution image spectroradiometer aerosol optical thickness and particulate matter concentration in this period were higher than without dust storm period. The moderate resolution image spectroradiometer aerosol optical thickness values lower than 0.1 were acquired uncertainty level. Comparison of moderate resolution image spectroradiometer images/ terra calibrated radiances 5 minutes L1B swath 1 km and image red, green and blue showed that moderate resolution image spectroradiometer has limitation in retrieval of aerosol optical thickness from the dust storm with high concentration of particulate matter. This study reveals that the algorithm which is applied to refine the aerosol optical thickness is not able to recognize the amount of particulate matter in low and very high concentrations sensitively. No study has previously been conducted to investigate the accuracy of the moderate resolution image spectroradiometer particulate matter products.

Keywords: *Aerosol optical thickness; Air quality; Particulate matter; Uncertainty level*

INTRODUCTION

Both solid and liquid particles in the air with varying compositions and sizes are called particulate matter (PM). Airborne suspended particulate matters (SPM) are produced by natural and anthropogenic sources. Whilst natural sources consist of sea salt from the oceans, volcanic eruptions and windblown dust; anthropogenic sources include motor vehicle exhaust, heat and power generation, industrial processes and open burning activities (Kaufman *et al*., 2003; Feng, 2009; Abdulsalam *et al.*, 2011). Transformation of precursor emissions in the atmosphere such as SO_2 to Sulphates (Quan *et al*., 2008) and NO_x to Nitrates (Wang *et al*., 2006) may also cause SPM. PM_{10} and $PM_{2.5}$ are the general terms to describe respirable particles of less than 10 and 2.5 µm in size, (Krewski *et al*., 2000). PM_{10} and $PM_{2.5}$ may cause harmful effects on human health (Adamson *et al*., 1999; Williams *et al*., 2003; WHO, 2005; Yassin and Almouqatea, 2010), because they are small enough to penetrate the upper and lower parts of the human respiratory system (Liu and Huza, 1995). The range of particles from 4 µm to 10 µm is classified as thoracic and is generally trapped in the larynx (Thurston *et al*., 1994). Deposit of SPM is another environmental effect especially when SPM is deposited

*Corresponding Author Email: *j_aman2005@yahoo.com*
Tel./Fax: 6019 6183 743

onto soil. When a high amount of SPM is deposited, due to their chemical composition, they may influence nutrient balance and acidity of soil (Herut *et al*., 2001; Yun *et al*., 2002; Odabasi *et al*., 2002; Hooshyari *et al*., 2009). The high amount of SPM in the air is a major problem in most parts of Asia. In many cities likes Beijing, Changchun, Kanpur, and Lucknow, the annual average values of total suspended particulate (TSP) exceeded 300 μg/m^3 (Baldasano *et al*., 2003). Seinfeld and Pandis (1998) showed that the absorption and scattered solar radiation can also reduce atmospheric visibility. Furthermore, SPM can also interact with the earth's radiation energy balance and affect the global climate change (Garland *et al*., 2008; Roshan *et al*., 2010). Traditional PM_{10} measured by ground station requires a large budget to install and maintain. In the last decade, advancement in remote sensing technology especially troposphere remote sensing created a new way of atmospheric pollution monitoring. Electromagnetic radiation is used to acquire information in remote sensing without being in physical contact with the subject (Martin, 2008). Measurements reflecting solar radiation at the top of the atmosphere are used for satellite aerosol remote sensing (Liu, 2008).

The moderate resolution imaging spectroradiometer (MODIS) onboard NASA's Aqua and Terra satellites is able to measure columns aerosol loading from the surface to the top atmosphere named aerosol optical thickness (AOT). Terra and Aqua satellites were launched on 18 December 1999 and on 4 May 2002 respectively, by the National Aeronautics and Space Administration (NASA). Both satellites orbit the Earth from pole to pole, covering most of the globe every day. Terra and Aqua pass equator at 10:30 am local and 1:30 pm local time respectively (Chu *et al*., 2003). Studies on the relationship between satellite-derived AOT and particulate matter in troposphere measured by ground stations have been undertaken (Chrysoulakis *et al*., 2003; Wang and Christopher, 2003; Sohrabinia and Khorshiddoust, 2007; Kampe, 2008). MODIS image and AOT were utilized to detect forest fire smoke (Kaufman *et al*., 2003; Gupta *et al*., 2007; Mazzoni *et al*., 2007). This paper emphasizes the accuracy assessment of MODIS particulate matter products such as AOT and images during dust storms. Thus, the objective of this paper is to determine the uncertainty levels of MODIS AOT for the evolution of PM_{10} concentration in Sanandaj from May 2009 to May 2010.

MATERIALS AND METHODS

Sanandaj is the capital of Kurdistan province in Iran and is located in the west of Iran (Fig. 1). The study area frequently receives dust storms from Saudi Arabia and Iraq (Fig. 1).

PM_{10} mass concentration and MODIS AOT were used in this research. MODIS collects data from land, atmosphere and ocean in three different spatial resolutions (bands 1 and 2 have 250 m, 3 to 7, 500 m and 8 to 36, 1 km). Spatial resolution and derived data in 36 spectral bands range from 0.4 to 14.5μm according to different geophysical parameters (NASA, 2009). Seven of these bands range from 0.47 μm to 2.13 μm devised to retrieve aerosol characteristics, over ocean and land. All of the seven wavelengths 0.47–2.13 μm over ocean and two wavelengths 0.47, and 0.67 μm over land are used to provide AOT (Remer *et al*., 2005). Daily AOT at 0.55 μm wavelength product onboard Terra satellite was utilized from May 2009 to May 2010.

These data have hierarchical data format (HDF) which can include text files, charts and tables (NASA, 2009). HDF files were viewed using HDF explorer. Geographical coordinates and PM_{10} data tables were opened respectively. The table of each data set which comprises numerous pixels in columns and rows was arranged in a column using macro in MS Excel. Visual basic program was utilized for running the model in macro. In this way, the data from each table are arranged in a column; subsequently corresponding pixel data in all tables were arranged in a row. Therefore, tables listed in columns and records of columns represent the pixel of each table in the HDF files (Sohrabinia and Khorshiddoust, 2007).

Another Visual basic program was written to find those coordinates situated inside Sanadaj area. Each pixel of level 2 AOT products has a 100 km^2 resolution. Ichoku *et al*. (2002) showed that MODIS pixels are more reliable when the 50 × 50 km^2 (5 × 5 pixels) average over PM_{10} stations is used. Real time of PM_{10} mass concentrations measured through Department of the Environment (DOE) and were compared with MODIS AOT. Both data stratified to the three sections, annually, with and without dust storm periods. The comparison of MODIS AOT and real-time of ground stations was undertaken using non-linear correlation coefficient with polynomial equation. MODIS images including RGB and (MOD021KM) were geo-referenced using PCI Geomatica version 9.2 and were matched with Iran map using Arc GIS version 9.2.

MOD021KM is a MODIS level-1B product which is used for detection of range fire smoke (Gupta *et al*., 2007). Iranian Ambient air qualities published by DOE were followed as comprising daily and annual standards for PM_{10}. According to these standards, the amount of PM_{10} should be less than 90 µg/m^3 on daily basis, and the monthly mean should be less than 40 µg/m^3.

RESULTS AND DISCUSSION

PM_{10} pollution in Sanandaj and other cities in the west of Iran is due to Suspended Particulate Matters (SPM) of dust storms. Sanandaj region is suitable for performing accuracy assessment of MODIS products related to PM_{10} because of the significant differences in the amount of the PM_{10} mass concentration in the atmosphere between dust storm event and normal day. Wind erosion in desert of Northern Saudi Arabia, Western Iraq and Eastern Syria were responsible for dust storms in the study area (Fig. 1). As a result, the west and south west of Iran experiences highly intense dust storms especially during dry season. Severe dust storms occurred from 4 July 2009 to 10 July 2009 and the averages of PM_{10} in Sanandaj were 1115 and 2976 µg /m^3 (DOE, 2009). The PM_{10} concentration reached a maximum of 5616 µg/m^3 at 2 a.m. 5 July 2009. AOT value and amount of PM_{10} at the real time and 24 hourly mean during the dust storm from 4 July 2009 to 10 July 2009 are shown in Table 1.

As Table 1 shows, the trend of AOT value and PM_{10} in both real time and 24 hourly mean is not similar. AOT for 5, 6 and 7 July were not acquired when their PM_{10} means were 2867, 786 and 456 µg/m^3, respectively. The missing AOT data may are due to cloud presence (Nicolantonio *et al*., 2007). Extracting AOT value from MODIS data needs powerful processing operations using special algorithms (Sohrabinia and Khorshiddoust, 2007).

King *et al*. (2003) described the effect of cloud cover on missing MODIS AOT data. In this study, the algorithm that was run for AOT product might have not run on cloud pixels based on the cloud mask of MODIS on 5, 6 and 7 July 2009. The non-linear correlation coefficient (NLCC) between MODIS AOT and real time of PM_{10} mass concentration in Sanandaj from May 2009 to May 2010 is shown in Fig. 2 (Hutchison *et al*., 2005). The result showed a low correlation coefficient (0.21). Correlation analyses were also performed to determine any relationship between satellite observations and PM_{10} mass during the periods with dust storms in June and July 2009 and without dust storm from August 2009 to May 2010.

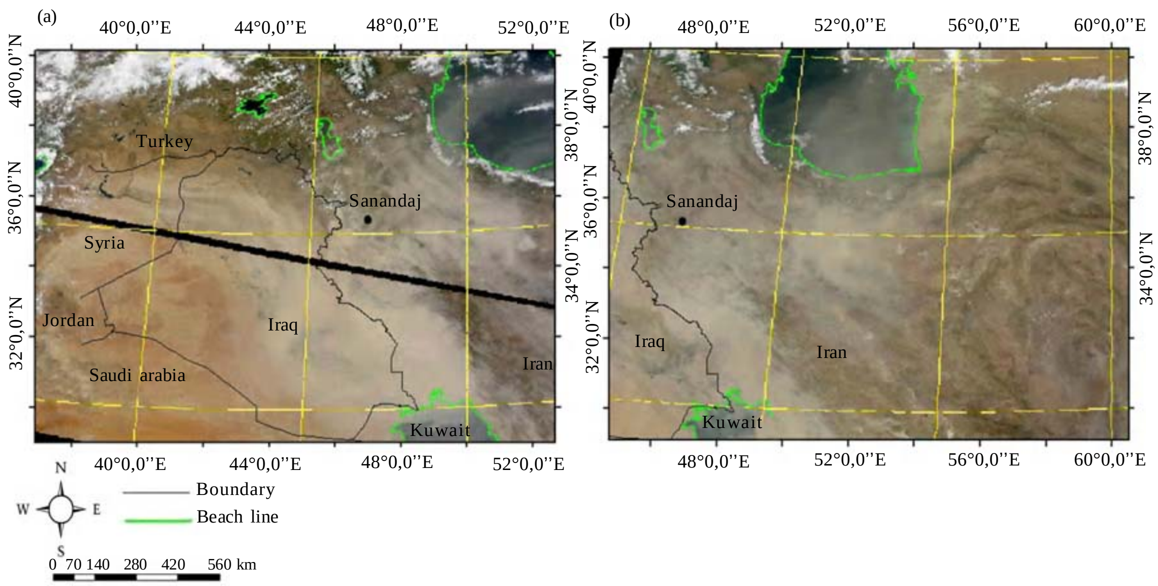

Fig. 1: Sanandaj geographical position in west of Iran. (a) The dust storm created by west winds in Iraq. (b) The dust storm created by southwesterly winds in Saudi Arabia

NLCC between real time of PM_{10} and MODIS AOT during dust storm and without dust storm periods are presented in Figs. 3 and 4, respectively. The correlation coefficient in dust storm period (0.34) was higher than that of without dust storm period (0.06). NLCC was obtained in Sanandaj (0.34) during dust storms period. The annual NLCC values (Fig. 2) and those of the dust storms period (Fig. 3) are consistent with previous findings in the United States (Wang and Christopher, 2003; Engeli-Cox *et al*., 2004) and Sydney, Australia (Gupta *et al*., 2007). Engeli-Cox *et al*. (2004) and Gupta *et al*. (2007) used linear correlation coefficient (LCC) in the analysis and obtained LCC values around 0.3. They also concluded that MODIS data are a superior data set for studying PM air quality over a large area. Despite the high AOT values due to dust storms in June 2009, in most of the cases, the AOT values derived were lower than 0.1 (Fig. 2). The AOT values lower than 0.1 shown in Fig. 3 were obtained in July 2009 (Fig. 4).

Despite high PM_{10} concentrations during dust storms in July 2009, AOT values were low and also the trend of AOT value and PM_{10} mass concentration were not the same. This finding suggests that there is no distinct relationship between the AOT value and PM_{10} mass concentrations in Sanandaj which decreased the NLCC value. NLCC between AOT values and PM_{10} was found 0.06 in without dust storm period (Fig. 5). This reveals that MODIS AOT values lower than 0.1 are uncertainty level for estimating PM_{10} mass concentration in Sanandaj.

The corresponding AOT at 55 μm in the RGB images on 5, 6, 8 and 9 July 2009 are shown in Figs. 6a, b, c and d, respectively. The AOT data were not found for Sanandaj coordinate system by MODIS on 5 and 6 July (Figs. 6a and b). Fig. 6. RGB images of MODIS during a big dust storm in Sanandaj. (a), (b), (c) and (d) represent the amount of PM_{10} on 5, 6, 8, and 9 July 2009.

Figs. 6c and d show the good detection of MODIS RGB images on 8 and 9 July 2009 according to Sanandaj coordinate system. AOT values of more than 1 are considered haze pixel and assigned red. The amount of PM_{10} measured by ground station on 8 and 9 July 2009 are in agreement with Figs. 6c and d which were obtained 278 and 242 μg /m³, respectively.

MODIS image products

Environmental information derived from MODIS L1B measurements offer a comprehensive and unprecedented look at terrestrial, atmospheric, and ocean phenomenology for a wide and diverse community of users throughout

Table 1: AOT values and amount of PM_{10} at the real time and 24 hourly mean during the dust storm from 4 to 10 July 2009

Days (July 2009)	AOT value	PM_{10} μg /m³ (real time)	PM_{10} μg /m³ (24 h mean)
4	1.3	999	1115
5	–	3294	2867
6	–	820	786
7	–	510	456
8	0.53	203	271
9	0.38	217	247
10	0.58	156	208

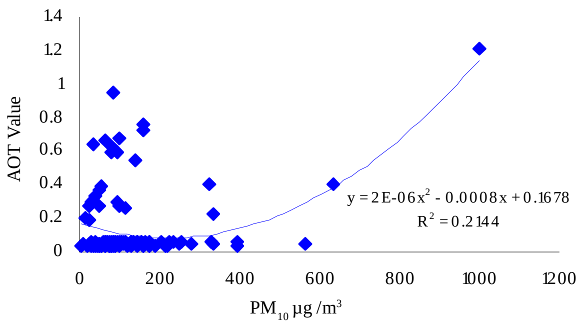

Fig. 2: NLCC between MODIS AOT and PM_{10} mass concentration in Sanandaj from May 2009 to May 2010

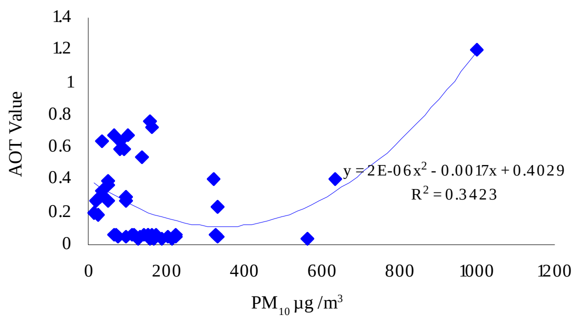

Fig. 3: NLCC between MODIS AOT and PM_{10} mass concentration during June and July 2009 in Sanandaj

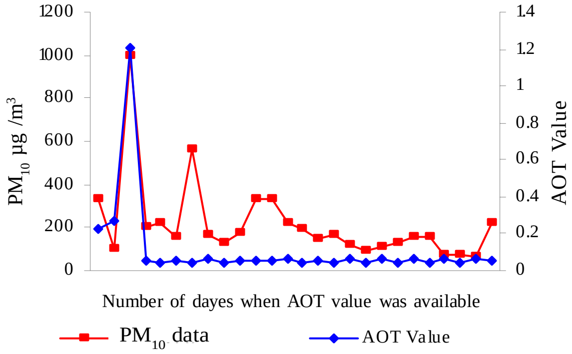

Fig. 4: Time series analysis of AOT value and PM_{10} mass concentration during July 2009 in Sanandaj

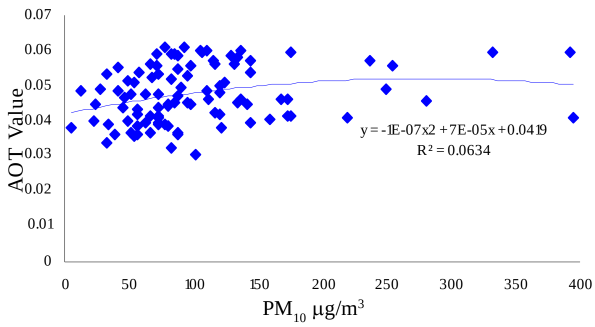

Fig. 5: NLCC between MODIS AOT and PM_{10} concentration from August 2009 to May 2010 in Sanandaj

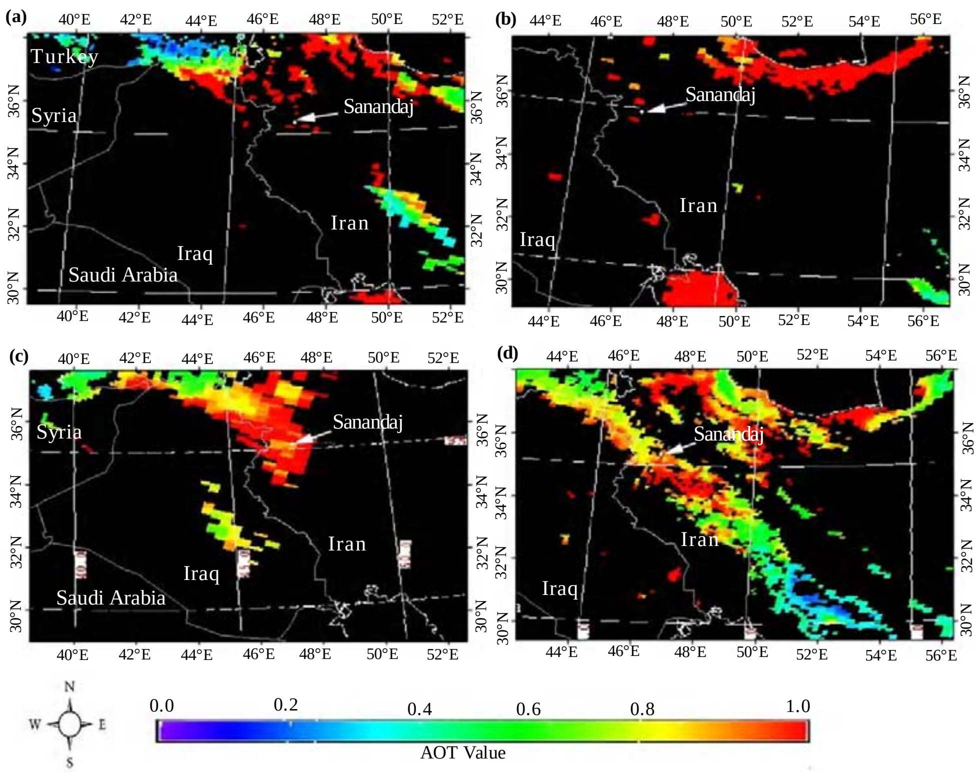

Fig. 6: RGB images of MODIS during a big dust storm in Sanandaj. (a), (b), (c), and (d) represent the amount of PM_{10} on 5, 6, 8 and 9 July 2009

the world. The Short name for this product is MOD021KM (NASA, 2010). MOD021KM was utilized to show the dust storm on 5, 6, 8 and 9 July 2009 in Sanandaj (Fig. 7).

MOD021KM image products of MODIS illustrated the area covered by dust storm better than AOT and RGB products of MODIS. Distribution and move direction of dust storm were shown clearly in MOD021KM images on 5 and 6 July. Concentration of PM_{10} in south west of Iran was more than that of other areas in Figs. 6a and b. The Zagros Mountain range in the east of this area prevented the dust storm from

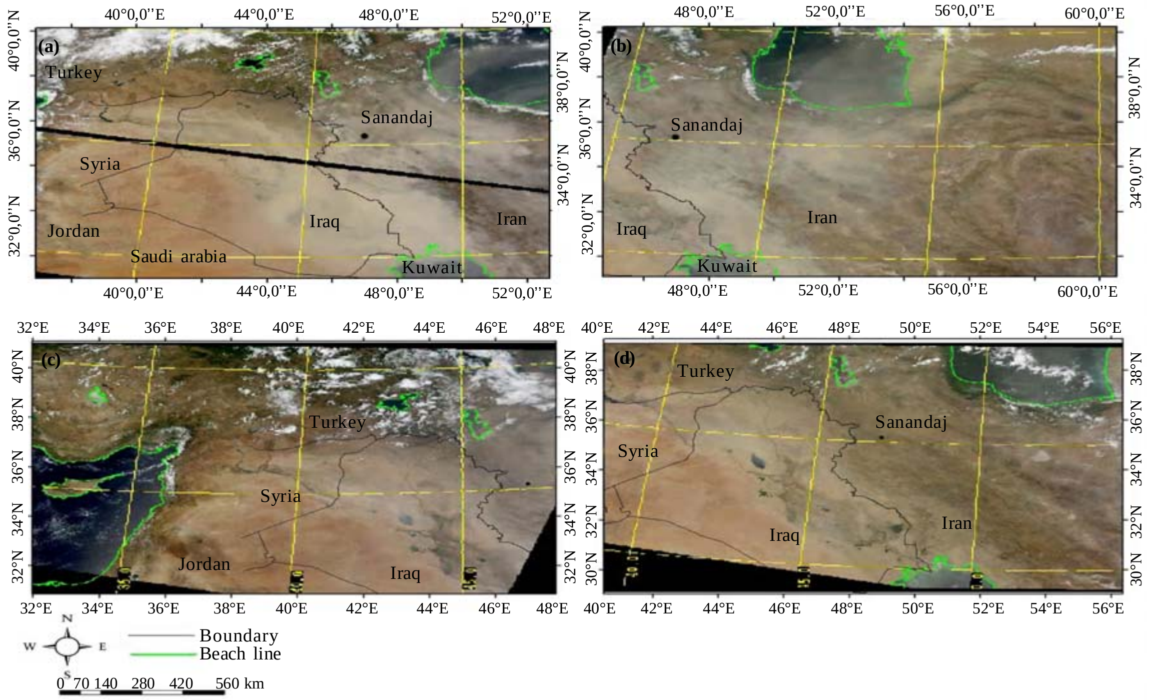

Fig. 7: Dust storm detected by MOD021KM image over Iraq, Kuwait, and Iran. (a), (b), (c) and (d) show dust storm on 5, 6, 8 and 9 July 2009, respectively

moving to the center of Iran resulting in the accumulation of particulate matter in south west of Iran. The low elevation of the Zagros Mountain range in west allowed for an uninterrupted movement of dust storm in this area compared to central Iran (Figs. 7a and b). Figs. 7a and b show a strikingly high concentration of PM_{10} on 5 and 6 July compared to 8 and 9 July in Figs. 7c and d. But in addition to Sanandaj, MODIS AOTs were not acquired for many parts of Iran and Iraq covered by dust storm (Figs. 6a and b) on 5 and 6 July. Cloud covers were not observed over Sanadaj and other parts of Iran and Iraq during 5, 6, 8 and 9 July (Fig. 7). Therefore, clouds did not affect MODIS AOT retrieval on 5 and 6 July. It can be assumed that MODIS is effective in retrieving AOT from dust storm with PM_{10} low concentration (Figs. 6c and d) compared to dust storm with a high PM_{10} concentration (Figs. 6a and b).

CONCLUSION

In the last few years, suspended particulate matter caused by dust storms has become the subject of environmental concern in west and south west of Iran. The reason is that on 5 July 2010 dust storms have led to increase in concentrations of PM_{10} by over 62 times as much as those on the same day in July 2009 in Sanandaj area. The accuracy of MODIS products in detecting PM_{10} was assessed in this research. The MODIS AOT data from May 2009 to May 2010 and their corresponding PM_{10} in real time measured by ground station site in Sanandaj were utilized. The data were stratified to annual, dust storm and without dust storm periods. Dust storms over the study area and other parts of Iran and Iraq were detected using MODIS MOD021KM images. The validation results indicated that there was no clear relationship between MODIS AOT and amount of PM_{10} at ground. NLCC for annual validation was obtained (0.21). The validation result in dust storm period was higher compared to without dust storm period. AOT values in without dust storm period were lower than 0.1. The NLCC results for without dust storm period showed that AOT values lower than 0.1 were of an uncertainly level. MOD021KM showed cloudy cover did not affect AOT non-retrievals during the enormous dust storm on 5 and 6 July 2009 in the study area. The findings of the study led the researchers to conclude that MODIS image MOD021KM is useful in investigating distribution and direction of dust storm but MODIS AOT values have an uncertainty level when the amount of PM is low or very high. Further studies are needed to describe the uncertainty level of AOT value when the amount of PM concentration is high.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Mrs. Kazhal Habibzadeh from Sanandaj Environment Protection Organization and also appreciate the Institute of Advance Technology of Universiti Putra Malaysia for their comments on remote sensing analysis.

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AUTHOR (S) BIOSKETCHES

Amanollahi, J., Ph.D. Scholar, University Putra Malaysia, Environmental Quality and Conservation. E-mail: *j_aman2005@yahoo.com*

Kaboodvandpour, S., Ph.D., Assisstant professor, Kurdistan University, Iran. E-mail: *kaboodvandpour@yahoo.com*

Abdullah, A. M., Associate professor, University Putra Malaysia. E-mail: *amakmom@env.upm.edu.my*

Firuz Ramli, M., Associate professor, University Putra Malaysia. E-mail: *firuz@env.upm.edu.my*

How to cite this article: (Harvard style)
Amanollahi, J.; Kaboodvandpour, S.; Abdullah, A. M.; Firuz Ramli, M., (2011). Accuracy assessment of moderate resolution image spectroradiometer products for dust storms in semiarid environment. Int. J. Environ. Sci. Tech., 8 (2), 373-380.